BOUNDARY LAYER TEMPERATURE RECOVERY FACTOR ON A CONE AT NOMINAL MACH NUMBER SIX

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BOUNDARY LAYER TEMPERATURE RECOVERY FACTOR ON A CONE AT NOMINAL MACH NUMBER SIX

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The author also wishes to express his appreciation to Mrs. Gerry Van Gieson for typing the thesis.

ABSTRACT

An investigation was conducted to determine the temperature recovery factors for laminar boundary layer on a cone at free stream Mach numbers from 5.6 to 5.9. The investigation was conducted in the GALCIT 5" x 5" continuous-flow, closed-circuit wind tunnel (Leg No. 1). Two twenty degree cone models about three inches in length were used. One model was composed of a ceramic core with a thin (0.010" to 0.015") steel surface, and the second was a hollow copper shell of 0.005" thickness.

One-phase and two-phase (condensation) flow conditions were investigated. Temperature recovery factors were determined from the data obtained from the tests conducted with one-phase airflows. The ratios of the temperatures recovered on the cone surface to the respective stagnation temperatures were computed from the data obtained in the two-phase airflow investigations and were compared with these ratios for the one-phase airflows.

The local temperature recovery factors for the laminar boundary layer were determined to be 0.844 ± 0.008 for Reynolds numbers from 2.1×10^4 to 5.4×10^5. For this range of Reynolds numbers the recovery factor was found to be independent of the Reynolds number. The independence of the recovery factor on the Mach number was substantiated (by comparison with results of previous investigations at lower Mach numbers) for Mach numbers up to 5.9. The ratios of the temperature recovered on the cone to the stagnation temperature were found to be the same for one and two-phase airflows.

The square root of the Prandtl number evaluated at the mean of the temperatures of the cone surface for the various flow conditions investigated was found to be less than one per cent lower than the mean of the experimental temperature recovery factors.

The results of this investigation are in agreement with those of previous investigations at lower Mach numbers and, within the limits of experimental accuracy, verify theoretical solutions.

TABLE OF CONTENTS

NOMENCLATURE

r_L	Local Temperature Recovery Factor (dimensionless)
	$r_L = \dfrac{T_s - T_L}{T_o - T_L} = \dfrac{T_s/T_o\left(1 + \frac{\gamma-1}{2} M_L^2\right)}{\frac{\gamma-1}{2} M_L^2}$
C_p	Specific heat at constant pressure for air (Btu/$^\circ$F lb)
k	Thermal conductivity coefficient (Btu/sec ft^2 $^\circ$F/ft)
M	Mach number (dimensionless)
p	Pressure (psfa)
Pr	Prandtl number, $gC_p\mu/k$ (dimensionless)
Re	Reynolds number, ux/μ (dimensionless)
t	Temperature ($^\circ$F)
T	Temperature ($^\circ$R)
u	Velocity (fps)
x	Distance from tip along ray of cone (ft)
γ	Ratio of specific heats, $\gamma = C_p/C_v$ = 1.40 (dimensionless)
μ	Absolute viscosity (lb sec/ft^2)
ρ	Air density (lb sec^2/ft^4)

Subscripts

a	Free stream (upstream of conical shock) condition
L	Local (just outside of boundary layer) condition
o	Stagnation condition
s	Cone surface condition

Superscript

'	Condition after passage through conical shock

I. INTRODUCTION

The attainment of supersonic velocities by current missiles and piloted aircraft and the possibility that within a few years the velocities may be in the hypersonic range have brought forth a new problem in aircraft design. This problem is the aerodynamic heating of high-speed vehicles.

Inasmuch as the strength and creep rate of the present standard aircraft structural metals are seriously affected by moderate temperature increases, the structural engineer must look for alloys having better high temperature properties. In order to do this intelligently he must be supplied with accurate information as to the temperatures to be expected at high velocities.

The purpose of this investigation was to determine experimentally the temperature recovery factor for a laminar boundary layer on the insulated surface of a cone. This recovery factor is a dimensionless quantity which represents the portion of the flow stagnation temperature which will be recovered on the surface of the cone.

In particular, it was desired to obtain the local temperature recovery factor. This recovery factor is defined as the ratio of the difference between the surface and local (just outside the boundary layer) temperatures to the difference between the stagnation and local temperatures.

The aerodynamic heating of an insulated surface is a function of the temperature of the airstream just outside the boundary layer, the amount of viscous energy dissipated in the boundary layer, and the radiation of the surface. The temperature of the air outside the boundary

layer is a function of the airflow local velocity, which in turn is a function of the deflection of the airstream due to the presence of the surface. Investigation of this parameter has been eliminated in this investigation by defining the recovery factor in terms of the local temperature instead of the free stream temperature upstream of the model. Therefore, the results determined were general and may be compared with the results of other investigations involving models of different shapes.

The viscous energy dissipated in the boundary layer is dependent on the character of the boundary layer. It has been found in previous investigations in this field that the recovery factors for a laminar boundary layer are essentially constant and independent of Mach number and Reynolds number. The recovery factors for a fully turbulent boundary layer have also been determined to be constant but higher than for the laminar case due to the eddy action in the boundary layer.

Previous experimental investigations (Refs. 1 - 6) have been conducted for free stream Mach numbers from one to five. The recovery factors for laminar boundary layers on cone models determined in these investigations have verified the theoretical result as postulated by Pohlhausen (Ref. 10) and others. The theoretical value for these recovery factors is close to the square root of the Prandtl number, which for the temperatures involved was about 0.845. It was, therefore, the purpose of this investigation to determine the laminar boundary layer temperature recovery factors for a Mach number of approximately six, to extend the existing data in the higher Mach number range.

II. DESCRIPTION OF APPARATUS AND TEST PROCEDURES

A. 5" by 5" Hypersonic Wind Tunnel

The investigation was conducted in Leg No. 1 of the GALCIT five-inch hypersonic wind tunnel with nominal Mach number six fixed nozzle blocks installed. This is a continuous-flow, closed-circuit wind tunnel powered by thirteen Fuller rotary compressors which were arranged for five compression stages. Fig. 1a shows the compressor plant control panel, the stagnation pressure indicator, and the stagnation temperature controller and indicator. Fig. 2 is a schematic diagram of the wind tunnel and power plant.

B. Instrumentation

Fig. 1b shows the temperature and pressure measuring equipment used in this investigation. A direct-reading, self-balancing Brown Potentiometer-Pyrometer, calibrated in degrees Fahrenheit, was used for the cone surface temperature measurements. The stagnation temperature was automatically recorded every forty-five seconds by a Minneapolis-Honeywell-Brown stagnation temperature controller-recorder. The nozzle and cone surface static pressures were measured on a silicone fluid manometer bank. The vacuum side of the manometer was maintained at a pressure of from two to four microns of mercury absolute.

C. Insulated Cone Models

Fig. 3 is a schematic diagram of the steel cone model. The thermocouples were located under the surface at distances from the tip measured along a ray of 0.49", 1.29", 1.89", and 2.44". Three static

pressure orifices were located as follows: the first 1.24" from the tip on one ray, the second 2.24" on the same ray, and the third 2.24" on the opposite ray. The cone vertex angle was 20.15°.

The core of the model is a casting composed of two parts stabilized zirconia to one part Sauereisen filler and cement. These materials were chosen for their low heat capacity, low thermal conductivity, and good high temperature properties. Both of the component materials can withstand temperatures in excess of 2000°F. No figures are available for the thermal conductivity of the combination. The low density and porous nature of the material, however, indicated lower thermal conductivity than for any other material considered.

The core casting contained the pressure orifice tubes, the model sting, and the four copper-constantin thermocouples. The thermocouple junctions were at the surface of the casting.

The metallic surface of the cone consisted of a flash coating of sprayed zinc and a heavier coating of sprayed 0.25 carbon steel. The conical surface was obtained by turning and polishing on a lathe, and the point of the cone was measured to have a radius of four to five thousandths of an inch. The machining properties of the low carbon steel made it virtually impossible to achieve a sharper point. The resultant thickness of the metallic surface could not be measured directly, but it was estimated to be of the order of ten to fifteen thousandths of an inch.

The copper cone model consisted of a copper shell with a wall thickness of approximately five thousandths of an inch. Four thermocouples, soldered to the inner surface of the shell, were located at the same distances along a ray as were those of the steel cone. Those

portions of the thermocouple lead-in wires that were exterior to the model were encased in a heavy saran tube.

D. Mounting Assembly

Figs. 4 and 5 show the details of the mounting of the model in the wind tunnel. The sting assembly was connected to the two vertical model-actuator rods by means of rolled melamine rods with a fibre glass filler. These plastic rods were used to minimize as much as possible any heat conduction from the model assembly to the tunnel walls.

The thermocouple wires were led through the side of the wind tunnel by means of a cannon plug mounted in a brass tube which projected from the side of the tunnel (Cf. Fig. 5). During the investigation a fan was turned onto the exterior of the brass tube and cannon plug. The resulting airflow kept the brass tube and cannon plug at a temperature very close to that of the room, and, therefore, the thermocouple effects between the inner and outer junctions of the cannon plug were virtually eliminated.

E. Test Outline and Procedures

The following procedure was followed for each flow condition investigated: The tunnel was run until the temperature of the surface of the cone, as indicated by the surface thermocouples, reached its equilibrium value. At this time the cone surface temperatures, the flow stagnation temperature, and the cone surface and tunnel test section static pressures were measured and recorded. Several complete sets of experimental data were recorded over a period of time to assure that equilibrium data were being obtained.

Data were obtained for the following flow stagnation temperatures and pressures:

T_o(°F)	p_o(psia)	Remarks
270	115.2	One Phase Flow
267	95.6	" " "
218	95.5	" " "
260	47.4	" " "
212	47.5	" " "
213	15.55	" " "
198	95.6	Boundary Between One- and Two-Phase Flow
117	95.6	Two Phase Flow
103	95.6	" " "

Schlieren pictures (Cf. Fig. 6) were taken of the flow about the model for representative flow conditions to provide a means for a qualitative investigation of the shock wave and the character of the boundary layer.

III. REDUCTION OF DATA

The following quantities were obtained from the experimental data:

T_s - temperature of the model surface

T_o - flow stagnation temperature

p_a - free stream static pressure

p_s - cone surface static pressure

p_o - flow stagnation pressure.

With the free stream Mach number (calculated using the p_a/p_o versus M relationship) and the cone vertex angle as parameters, the wave angle of the conical shock was determined from the MIT Tables of Supersonic Flow around Cones (Ref. 7). Assuming the stagnation pressure rise through a conical shock to be the same as that through a plane oblique shock for the same Mach number and wave angle, the pressure ratio p_o'/p_o was calculated. The ratio p_s/p_o was then calculated, and with this ratio the local Mach number, M_L, was calculated from the isentropic pressure relationship.

For computational purposes, the expression for the local temperature recovery factor was combined with the adiabatic energy equation and reduced to the following form:

$$r_L = \frac{T_s/T_o \left(1 + \frac{\gamma-1}{2} M_L^2\right) - 1}{\frac{\gamma-1}{2} M_L^2}$$

(γ is assumed constant and equal to 1.40)

An accuracy analysis (Cf. Appendix A) was made, considering all possible errors that might accumulate due to the limiting accuracy of the potentiometers, errors in manometer readings, and errors accumulating in the reduction of the experimental data. This analysis indicated that

if all the above errors were additive, the computed local temperature recovery factor might be in error by $\pm$ 1% or $\pm$ 0.008.

The free stream Reynolds number was computed on the basis of free stream density, velocity, and viscosity, and the lengths along the cone ray to the thermocouple locations. The Prandtl number was computed according to the method outlined by F. G. Keyes in Ref. 8.

IV. DISCUSSION OF RESULTS

A. Local Temperature Recovery Factor

The primary results of this investigation are presented in Figs. 7 and 8 and are summarized as follows:

$$r_L = 0.844 \pm 0.008$$

$$\text{for } Re_a = 2.1 \times 10^4 \text{ to } 5.4 \times 10^5$$

$$M_a = 5.58 \text{ to } 5.88$$

$$M_L = 4.78 \text{ to } 4.96$$

The temperature recovery factors plotted in Figs. 7 and 8 and indicated above represent an average of the recovery factors computed from the data for each thermocouple, for each flow condition, These averages were believed to be more indicative of the actual values than the individual calculated values would be, for the following reasons: It was difficult to read the stagnation temperature from the controller-recorder more accurately than to about one degree. This temperature as indicated by the controller had a tendency to drift sinusoidally at times as much as one degree in forty-five seconds. The controller-recorder printed this temperature only once every forty-five seconds; thus, the question as to which point to record during a data-taking run presented itself. Since several complete sets of data were recorded at random times for each flow condition, it was believed that the average of these data would be the best estimate of the actual conditions. Had this averaging process not been used, the variation in r_L would have been increased from $\pm$ 0.005 to $\pm$ 0.006.

The two thermocouples nearest the base of the model consistently indicated temperatures from three to eleven degrees higher than the forward two. Schlieren photographs were taken of the flow about the model so that the boundary layer could be checked visually for a possible occurrence of transition on the model. These photographs, however, indicated that the boundary was laminar over the entire conical surface (Cf. Fig. 6).

A second investigation was made with thermocouples on the model sting and sting support. A channel was scraped into the metal on the base of the cone so that no direct metallic path by way of the base existed between the sting and the cone surface. The thermocouples on the sting assembly indicated temperatures from thirty to forty degrees higher than on the cone. It was concluded that the apparent increase in the temperature at the base of the cone was due to heat conduction to the thermocouple junctions by way of the shorter thermocouple wires. This conclusion was born out when the conical surface of the model was immersed into boiling water and into ice water. In these cases, the forward two thermocouples indicated the correct temperatures and the two nearest the base indicated temperatures nearer room temperature. With the model, including part of the sting, completely immersed, all thermocouples indicated the correct temperature.

A third investigation was made using a copper cone model. The lead-in wires to this model were thermally insulated from the flow by a heavy saran tube. In this case, the temperatures indicated were quite consistent except for the last thermocouple, which was located about $\frac{1}{4}$" from the base plug.

In view of the above conditions, it was decided that only the data

obtained from the forward two thermocouples for the steel cone and from the forward three for the copper cone were representative of the actual temperatures at the cone surface.

B. Agreement with Existing Theory

Theoretical analyses have indicated that the temperature recovery factor for a laminar boundary layer should be approximately equal to the square root of the Prandtl number. However, the Prandtl number was maintained as an independent parameter in these analyses, and, therefore, the temperature at which this parameter should be evaluated was not specified. Fig. 8 presents the temperature recovery factors superimposed on plots of the square root of the Prandtl number versus temperature for the cone surface temperatures and the local temperatures. The experimentally determined recovery factors fell in the range between the square roots of the Prandtl numbers evaluated at the temperatures of the cone surface, $Pr_s^{\frac{1}{2}}$, and the air at the outer edge of the boundary layer, $Pr_L^{\frac{1}{2}}$. The experimental recovery factors, r_L, agreed with $Pr_s^{\frac{1}{2}}$ within 1.2%.

The values of the Prandtl number for the very low local temperatures (114° - 127° R) were computed according to the formulae used by Keyes (Ref. 8). The temperature range involved was below that for which the formulae for the air viscosity and heat conductivity were entirely valid. These computed values, however, represent the best available estimate of the Prandtl number at low temperatures.

C. Agreement with Previous Investigations

Previous investigations of the temperature recovery factors for

laminar boundary layers on cones (Refs. 1 - 4), for supersonic airflow, are summarized as follows:

Investigators	Mach No.	r_L
Winbrow (Ref. 1)	1.5 2.0	0.845 ± 0.008 0.855 ± 0.008
Eber (Ref. 2)	0.88 - 4.65	0.845 ± 0.008
des Clers; Sternberg (Ref. 3)	2.18	0.851 ± 0.007
Stine; Scherrer (Ref. 4)	2.0	0.845

These results agree with the results of this investigation within the limits of possible experimental and computational errors. From the foregoing, it was concluded that the recovery factor is not a function of Mach number for Mach numbers below approximately six. This conclusion is valid for Mach numbers up to six in wind tunnels where the temperatures are low enough that dissociation of the air does not occur and the ratio of specific heats, γ, is essentially constant.

The temperature recovery factors, as determined by previous investigations (Refs. 5 and 6) with flat plate models, are 0.881 and 0.884. DeLauer (Ref. 9) determined the recovery factor for a flat plate to be 0.858 for a Mach number of approximately 5.9 in the GALCIT 5" x 5" hypersonic wind tunnel. The discrepancy between the cone and flat plate results has not been satisfactorily explained.

D. Effect of Condensation

The results of calculations of the local temperature or the local Mach number, using the available two-phase relationships, are not sufficiently accurate for the calculations of the temperature recovery

factors. Therefore, the recovery factor for the two-phase flow conditions was not determined. However, it was noted that the ratios T_s/T_o, for the runs in which various finite degrees of condensation occurred, were the same as for the runs where the flow was entirely one-phase.

E. Miscellaneous Results

A very small static pressure rise was noted on the surface of the cone with increasing distance from the tip. The pressures were measured at two stations, one inch apart, along a ray of the cone. The static pressure rise did not exceed 0.33%. The pressure orifices were well downstream of the region affected by the leading edge shock wave-boundary layer interaction.

The shock wave angle was measured from the schlieren photographs and was found to agree, within the accuracy of measurement, with the shock wave angle as determined by potential theory (Ref. 7). The shock wave angle did not appear to be affected by the presence of condensation in the flow (Cf. Fig. 6).

F. Recommendations

In view of the difficulties encountered in this investigation, two specific recommendations are made with reference to model design and instrumentation. In the design of the model and components, great care must be taken to insure that the thermocouple lead-in wires are effectively insulated from the high temperatures of turbulent or wake regions downstream of the model. This must be done to minimize the heat flow in the thermocouple wires. Also, the stagnation temperature and the

cone surface temperatures should be obtained with the same measuring instrument so that there will be consistency in the readings. The value of interest in an investigation of this type is the ratio T_s/T_o rather than the absolute magnitude of either of the temperatures. If both temperatures are measured with the same instrument, the ratio T_s/T_o calculated would be essentially correct for small instrument errors.

V. CONCLUSIONS

The conclusions listed below were based on the results of this investigation except where otherwise indicated. It must be kept in mind that these conclusions were determined for flow conditions as encountered in the wind tunnel, where the flow conditions can be represented by the perfect gas laws and where dissociation of air due to high temperature does not occur.

1. The local temperature recovery factor for a laminar boundary layer on a cone is 0.844 ± 0.005 for Mach numbers from 5.6 to 5.9.
2. This laminar boundary layer recovery factor is independent of the Reynolds number for the range (2.1×10^4 to 5.4×10^5) investigated.
3. This recovery factor is also independent of the Mach number for Mach numbers less than approximately six. This conclusion was based on a comparison of results with those of previous investigations at lower Mach numbers.
4. The temperature recovery factor for a laminar boundary layer is approximately equal to the square root of the Prandtl number as postulated by theory.
5. The ratio, T_s/T_o, of the temperature recovered on the surface of the cone to the stagnation temperature is essentially the same for one and two phase airflows.

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APPENDIX A

ACCURACY ANALYSIS

The estimated maximum error of the individual measurements is as follows:

Measurement	Estimated Maximum Error	Basis of Estimate
Static Pressure - p	0.4 mm of silicone	Reading Error
Stagnation Pressure - p_o	less than 1%	Calibration of Gage
Cone Surface Temperature - T_s	1^oF	Limiting Accuracy of Pyrometer and Calibration of Model
Stagnation Temperature - T_o	3^oF	Calibration of T_o Probe and Reading Error

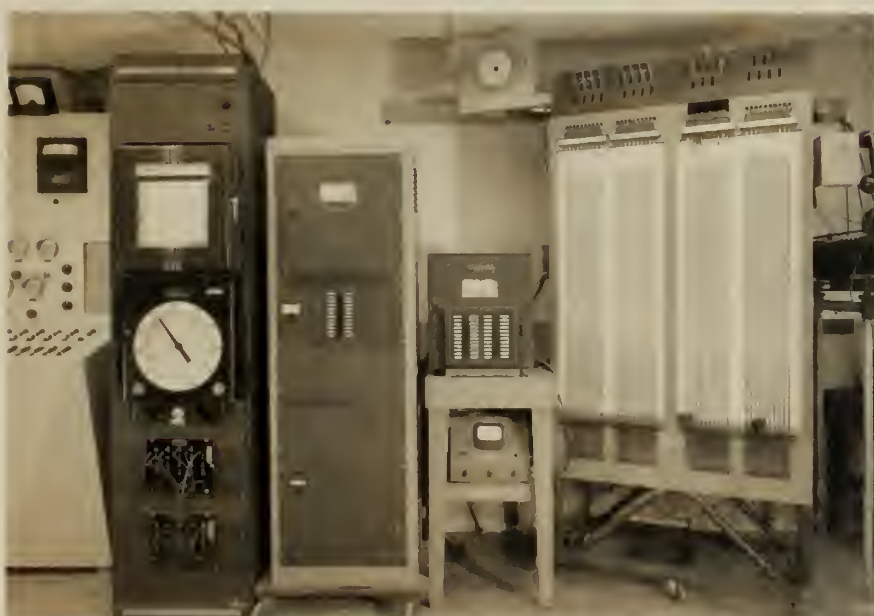
The accuracy of computed values, based both on the errors of the individual measurements and on the errors from the use of graphs, tables, etc., is as follows:

Quantity	Calculated Error
Free Stream Mach Number - M_a	less than 1%
Local Mach Number - M_L	less than 1%
Local Temperature Recovery Factor - r_L	$\pm$ 1% or $\pm$ 0.008

LIST OF FIGURES

Compressor Plant Motor and Valve Controls
Reservoir Pressure and Temperature Regulators
Plant Pressure and Temperature Indicators

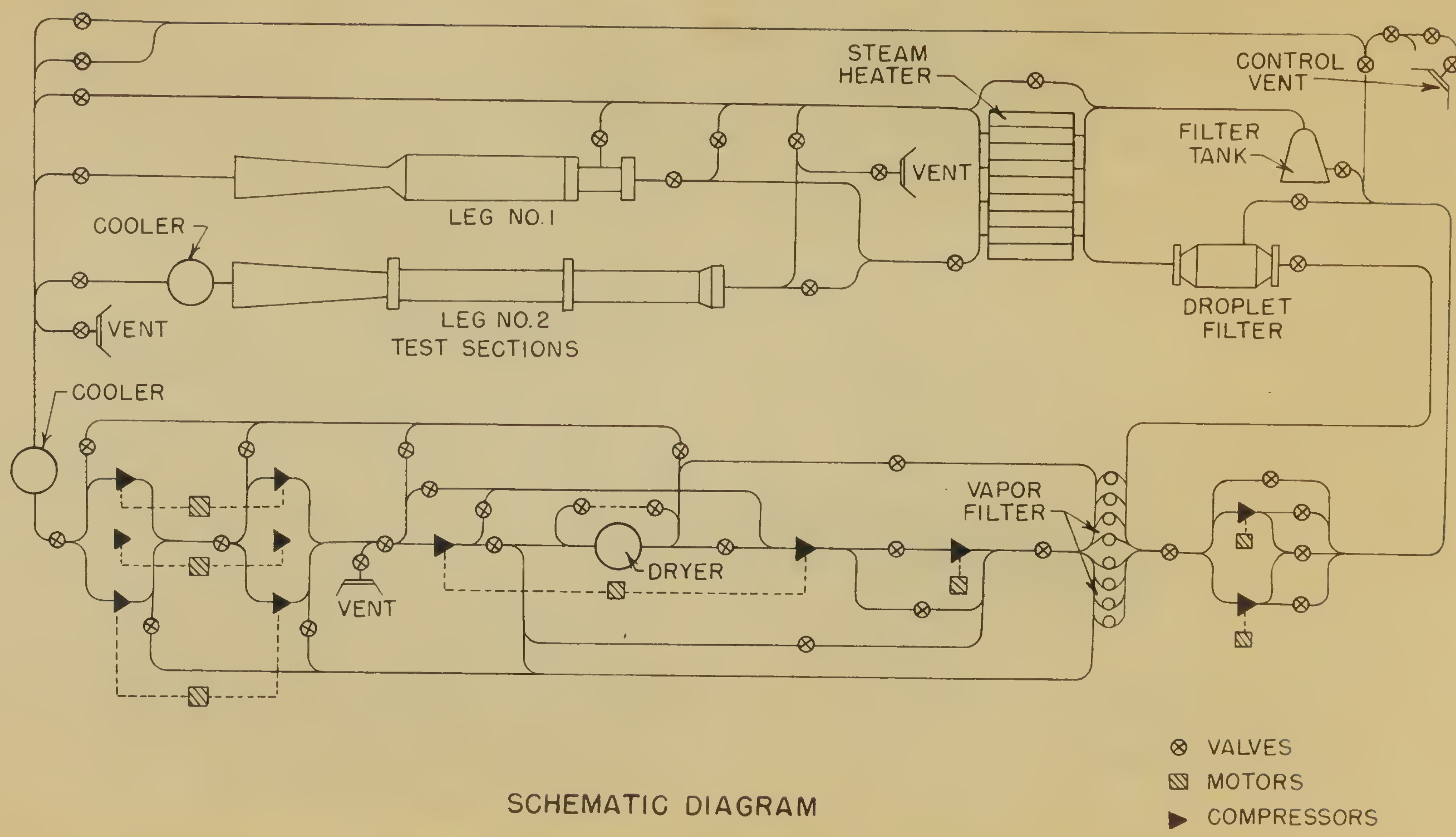
Fig. 1a



Test Section and Nozzle Block
Pressure and Temperature Instrumentation

Fig. 1b

GALCIT 5 x 5 IN. HYPERSONIC WIND TUNNEL
CONTROLS AND INSTRUMENTATION



SCHEMATIC DIAGRAM

OF GALCIT 5x5in. HYPERSONIC WIND TUNNEL INSTALLATION

FIG.2

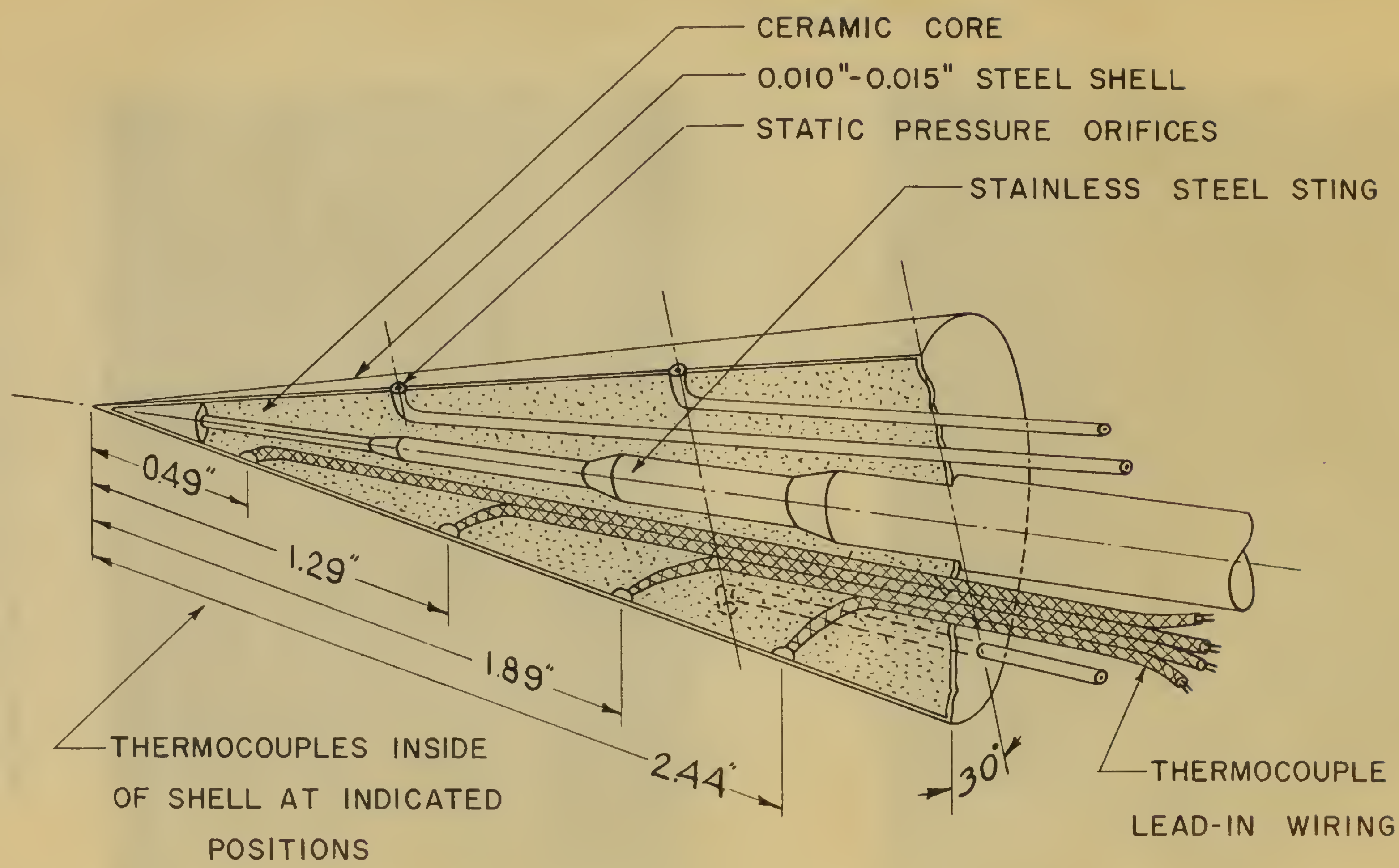


FIG. 3 TEMPERATURE RECOVERY CONE

Fig. 4a -- Cone Model

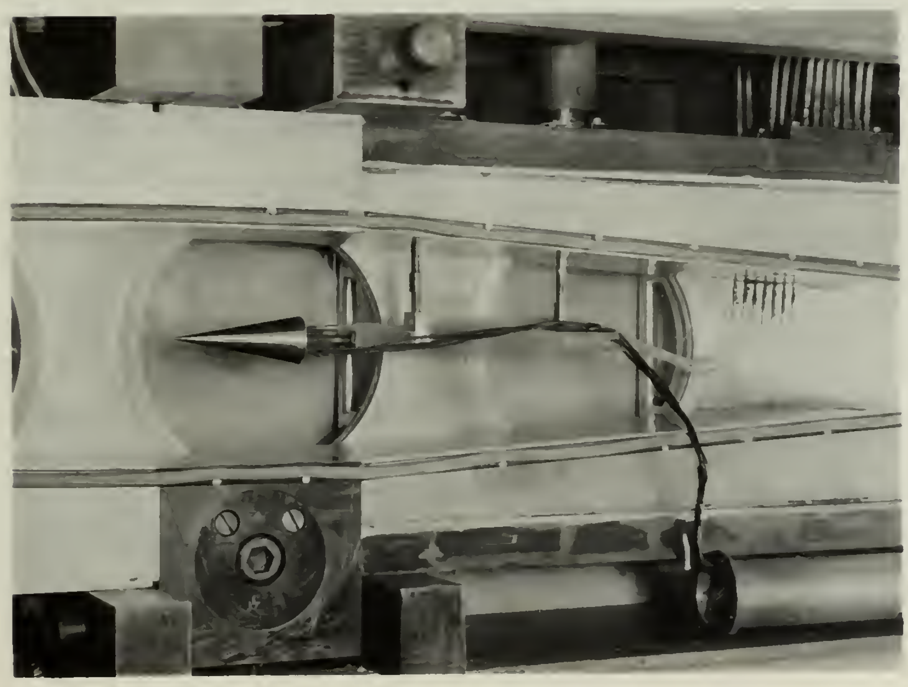
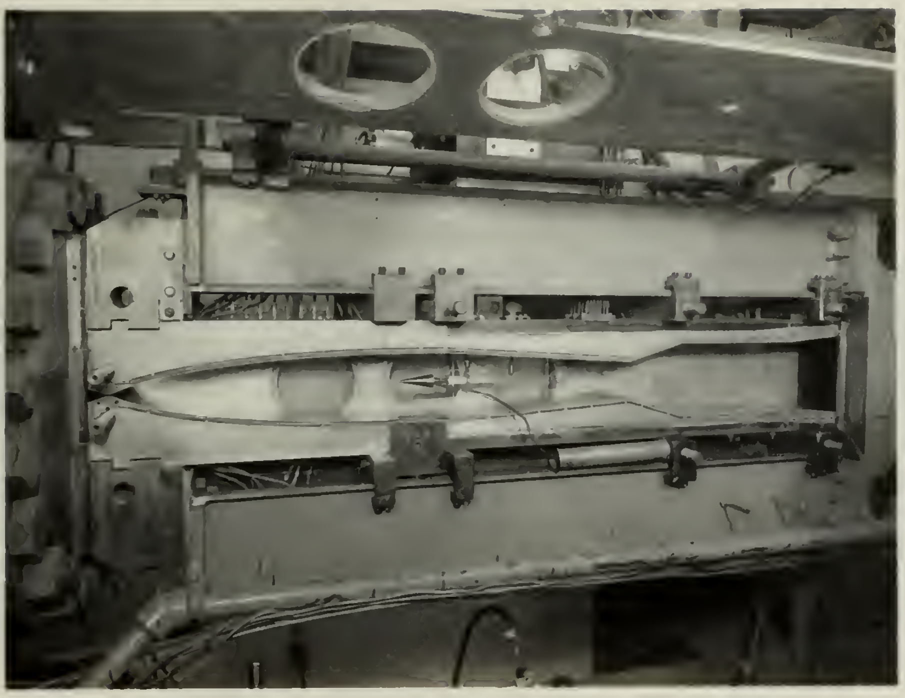


Fig. 4b -- Cone Model and Mounting Assembly

CONE MODEL AND MOUNTING ASSEMBLY



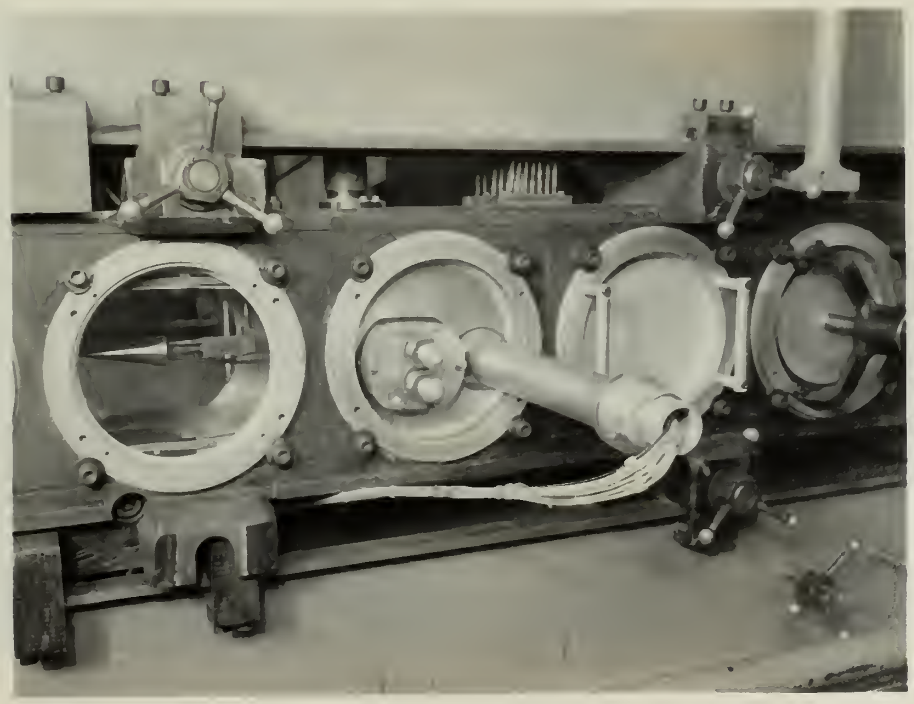


Fig. 5

TEMPERATURE RECOVERY CONE MODEL IN TEST SECTION

OF GALCIT 5" x 5" HYPERSONIC WIND TUNNEL

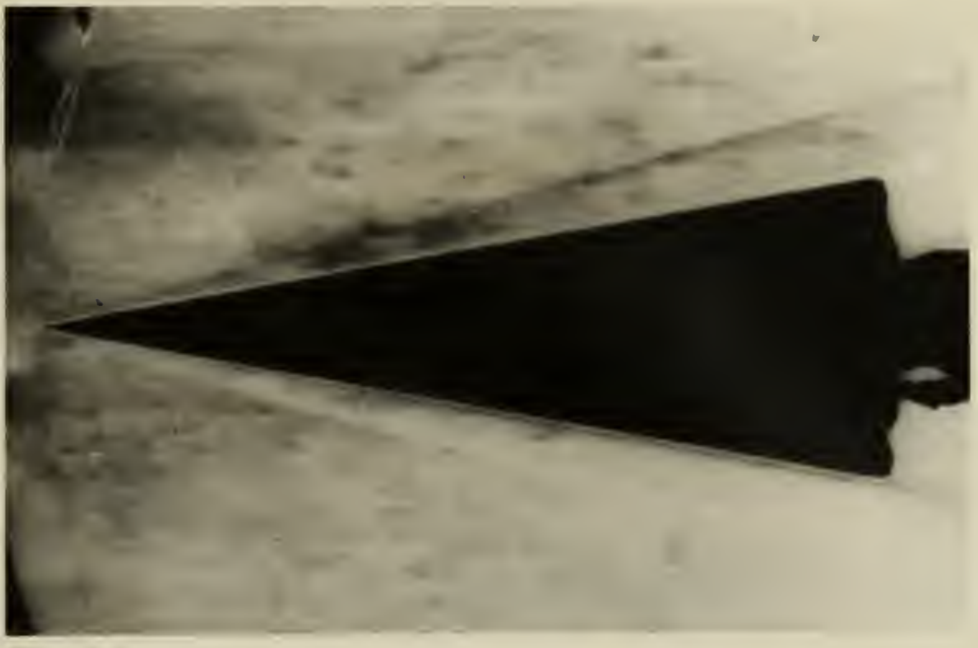


Fig. 6a -- One Phase Flow - $M \approx 5.9$
(p_o = 80 psig, T_o = 266°F)

Fig. 6b -- Two Phase Flow
(p_o = 80 psig, T_o = 147°F)

SCHLIEREN PHOTOGRAPHS SHOWING SHOCK WAVE

AND BOUNDARY LAYER

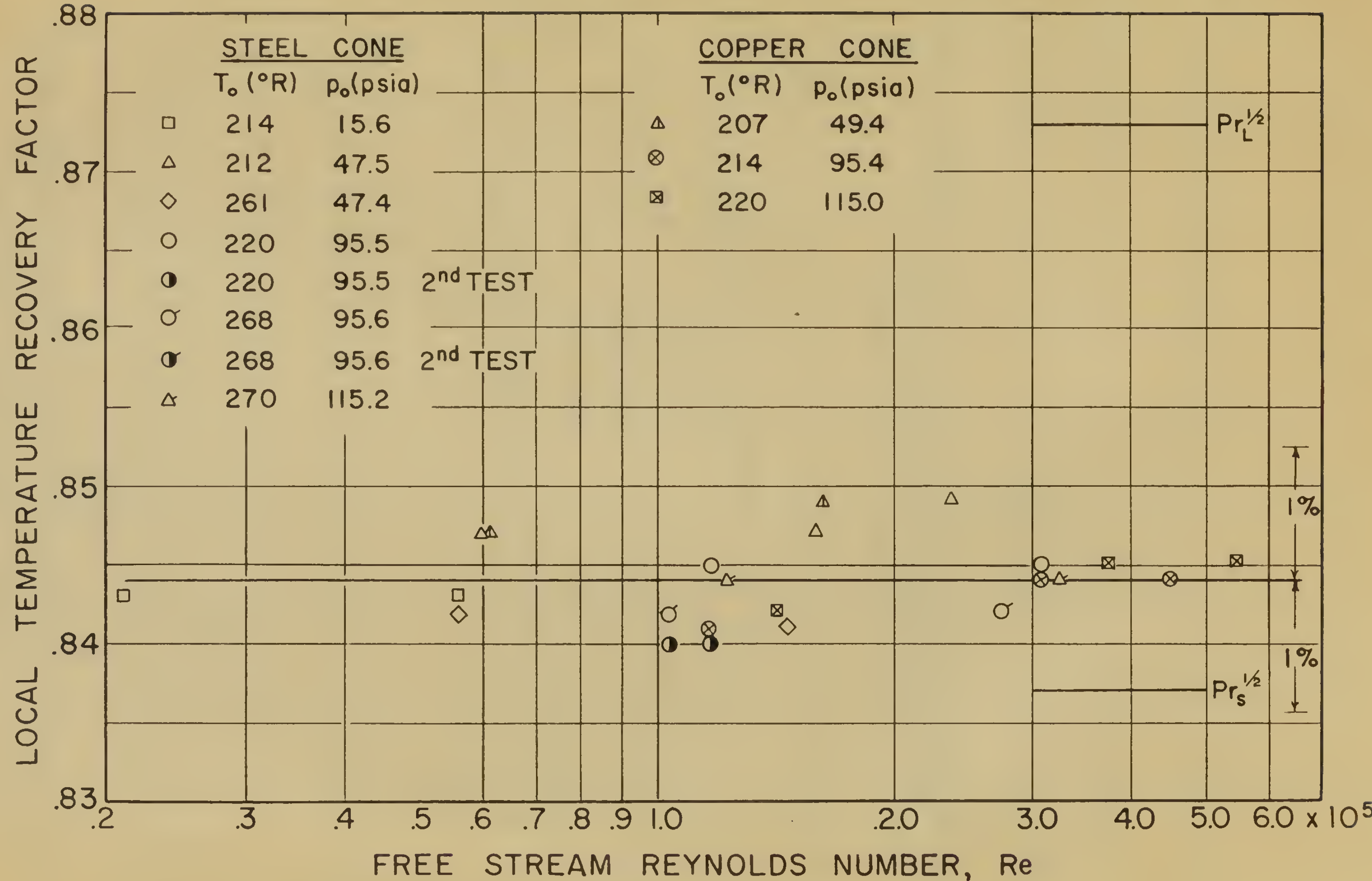


FIG. 7 EXPERIMENTAL TEMPERATURE RECOVERY FACTORS

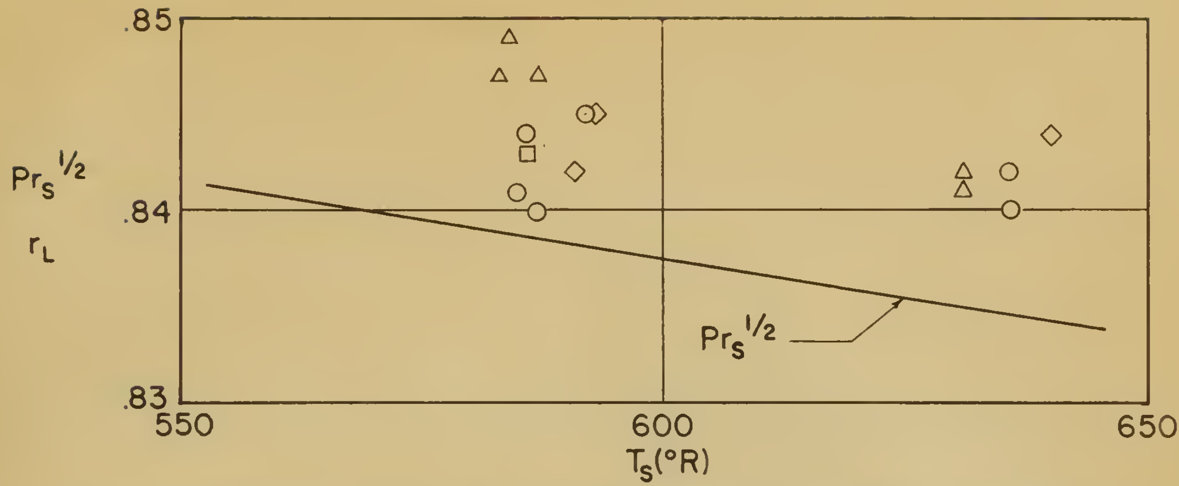


FIG. 8a SQUARE ROOT OF THE SURFACE PRANDTL NUMBER, $Pr_S^{1/2}$, AND LOCAL TEMPERATURE RECOVERY FACTOR, r_L, VERSUS SURFACE TEMPERATURE

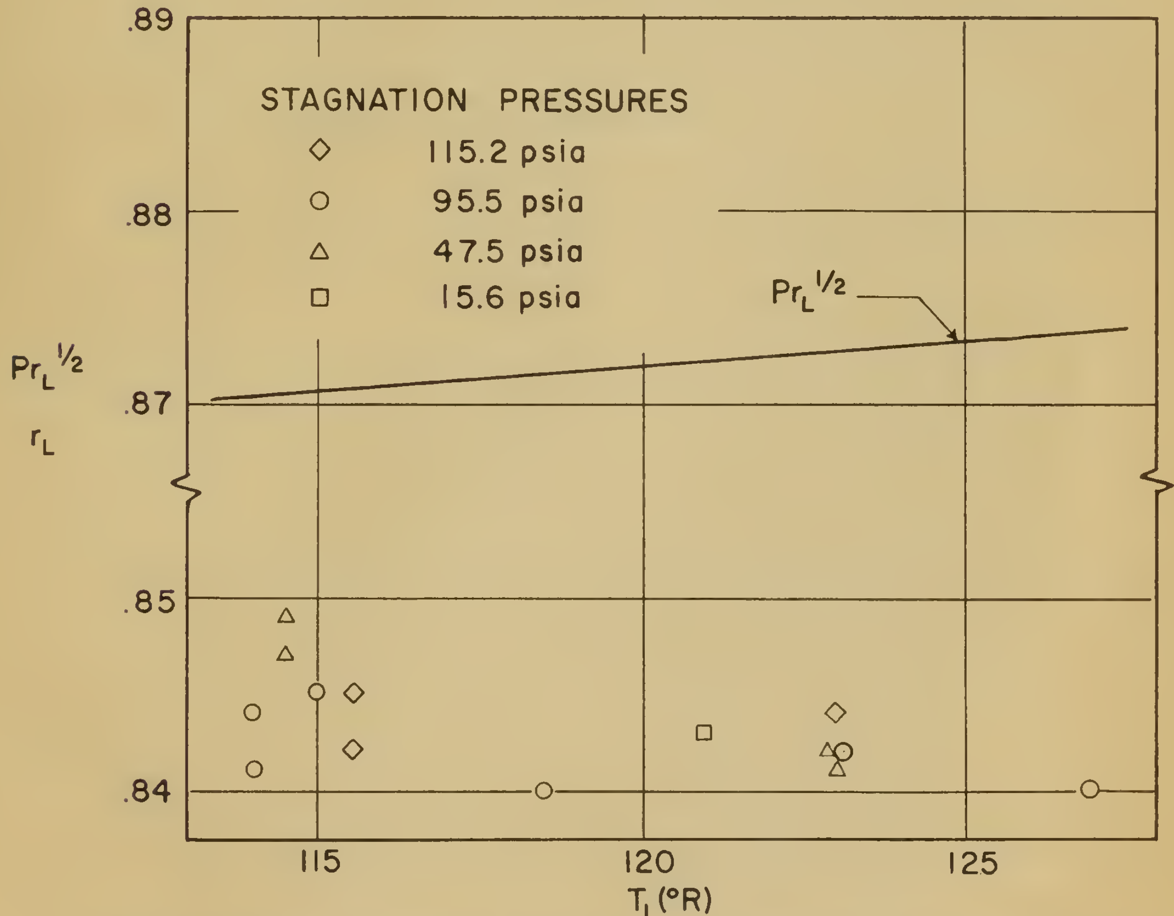


FIG. 8b SQUARE ROOT OF THE LOCAL PRANDTL NUMBER, $Pr_L^{1/2}$, AND LOCAL TEMPERATURE RECOVERY FACTOR, r_L, VERSUS LOCAL TEMPERATURE

Boundary layer temperature recovery factor on a cone at nominal mach number six.

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Boundary layer temperature recovery factor on a cone at nominal mach number six.